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Modelling the Action of Water on Dynamic Mechanical Properties of Wood

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Abstract—The influence of moisture on the acoustical properties of wood was analyzed by a rheological analogy. Matrix molecular mobility was quantified by eliminating the swelling contribution to longitudinal dynamic specific modulus (E'/γ) and loss tangent ($\tan \delta$).

Keywords: Vibrational properties, dynamic specific modulus, loss tangent, rheological model.

Modelling

The vibrational properties were analyzed using the model of Fig 1, with fibrils (f), matrix (m) and, air (a) disposed in parallel. Volume fractions v_f , v_m , and, v_a refer to the volume of wood stored in air-dry condition (60% RH and 20°C from oven-dried state, or 9% m.c.), taken as the “untreated” reference, so that $v_f + v_m + v_a = 1$. Wood is considered as “modified” by other humidity conditions, provoking a matrix volume increase Δv_m and specific gravity increase $\Delta \gamma_m$, related to the entire volume and specific gravity by assuming no volume change of lumens and a specific gravity of absorbed water equal to 1. Cellulosic fibrils are represented by a spring of rigidity $E_1 = v_f E_f$, amorphous matrix by a Maxwell two-element model with rigidity $E_2 = k(v_m + \Delta v_m)E_m$ and relaxation time $\tau_2 = s\tau_m$, with k and s indicating the effect of humidity on rheological properties of the matrix. Assuming viscoelastic linearity and a frequency high enough to ensure $(\omega\tau_m)^2 \gg 1$, so long as the glassy transition is exceeded, the expressions of the longitudinal specific modulus (E'/γ) and the loss tangent ($\tan \delta$) are:

$$E'/\gamma \approx \frac{v_f E_f + (v_m + \Delta v_m)kE_m}{v_f \gamma_f + (v_m + \Delta v_m)(\gamma_m + \Delta \gamma_m)} \quad ; \quad \tan \delta \approx \frac{(v_m + \Delta v_m)kE_m}{[v_f E_f + (v_m + \Delta v_m)kE_m]\omega s\tau_m}$$

In Fig. 2 the effect of water loss (5.5% m.c., corresponding to 35% RH) and water uptake (22% m.c., 95% RH) on $\log E'/\gamma$ and $\log \tan \delta$ were simulated using a wood with an air-dry specific gravity of $\gamma = 0.45$, corresponding to a cell wall specific gravity of 1.45 and a void volume fraction of 0.69. Choosing $v_f = v_m = 0.155$, $E_f = 134$ GPa, $E_m = 2$ GPa and $\tau_m = 1.91$ ms yields $E'/\gamma \approx 46.9$ GPa and $\tan \delta \approx 0.0049$, which is compatible with the previous data extrapolated to zero mean microfibrillar angle (MMA) and is indicated by the empty circle on the graph. The filled circle simulates only the effect of moisture expansion,

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i.e. with no modification of matrix properties ($k=s=1$). The parameter k , indicating the relative increase of matrix rigidity, was varied between approximately 0 and 10. Matrix softening was described by a *matrix mobility* factor $\mu=\log(k/s)$ ranging between -0.1 and $+0.1$.

Actual measurements on Sitka spruce (air-dry specific gravity 0.43) were shown on the same graph and were found to have lower E'/γ and higher $\tan \delta$ than the theoretical prediction because of the non-zero MMA. The dotted line shows the regression ($\log \tan \delta \approx -1.21 - 0.66 \log E'/\gamma$) derived from the previous measurements on softwoods in the same conditions, ending down-right on the theoretical untreated plot (empty circle) and initial data plots lie well in its vicinity. The amount of experimental shift from air-dry to either dry (35%) or wet (95%) conditions must be compared to the respective theoretical shifts simulated down-right. The sole effect of weight and volume increases (shift from empty to filled circle), in both cases, accounts for a part of the observed shift. The remaining part can be attributed to modification of matrix properties ($k \neq 1$ and $\mu \neq 0$). In theory, it can therefore be estimated that values of k and μ corresponds to the drying or wetting "treatments". In practice, in order to arrive at reliable estimates we need either to obtain data for a larger range of MMA and extrapolate to zero MMA, or to derive multiaxial equations taking into account the non-zero MMA. Previous data for various humidities and MMA suggest that extrapolating to zero MMA would not change much the $\log \tan \delta$ shift, or very slightly increase it, while it would remarkably reduce the $\log E'/\gamma$ shift. This allows to conclude that drying decreased the molecular mobility of the matrix ($\mu < 0$), and wetting increased it ($\mu > 0$).

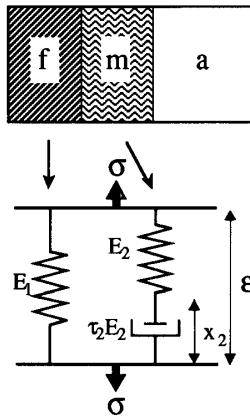


Fig. 1. Rheological model.
f: cellulosic fibril; m: amorphous matrix; a: air; σ : stress; ϵ , x_2 : strains; E_1 , E_2 : elastic moduli; τ_2 : relaxation time.

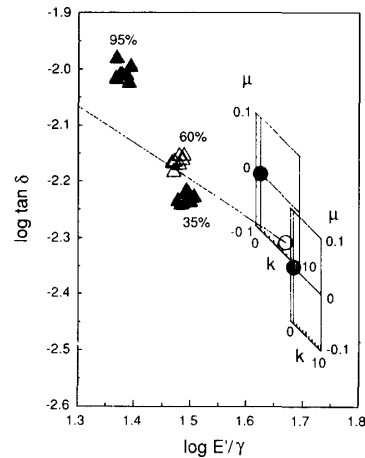


Fig. 2. Effect of water in the cell wall on the $\log E'/\gamma$ — $\log \tan \delta$ relationship. The broken line shows the experimental correlation for untreated specimens. Various values of relative increase of matrix rigidity (k) and mobility factor ($\mu = \log(k/s)$) were simulated.
 \triangle , \blacktriangle : experimental values; \circ , \bullet : theoretical plot for zero MMA.